IceCube/DeepCore, PINGU and MICA: Prospects for MeV-GeV Scale Physics in the Ice

Fundamental Physics at the Intensity Frontier
Rockville, Maryland
Nov-Dec 2011

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IceCube and PINGU Collaborations
and
Department of Physics
Penn State University

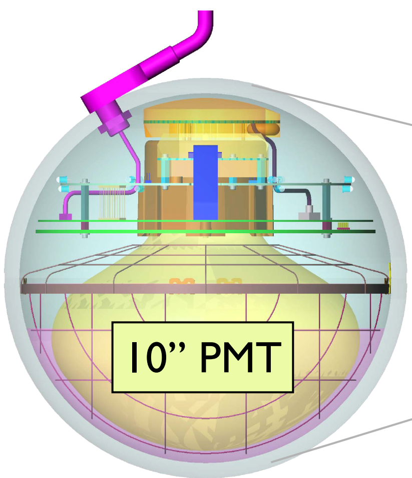
Outline

- IceCube and its DeepCore sub-array
  - Design, geometry, ice properties
  - Performance
  - Physics goals, first results
- Future plans
  - PINGU*
    - Possible design, physics goals
  - MICA**
    - Plausibility of multi-MTon MeV-GeV scale detector in the ice

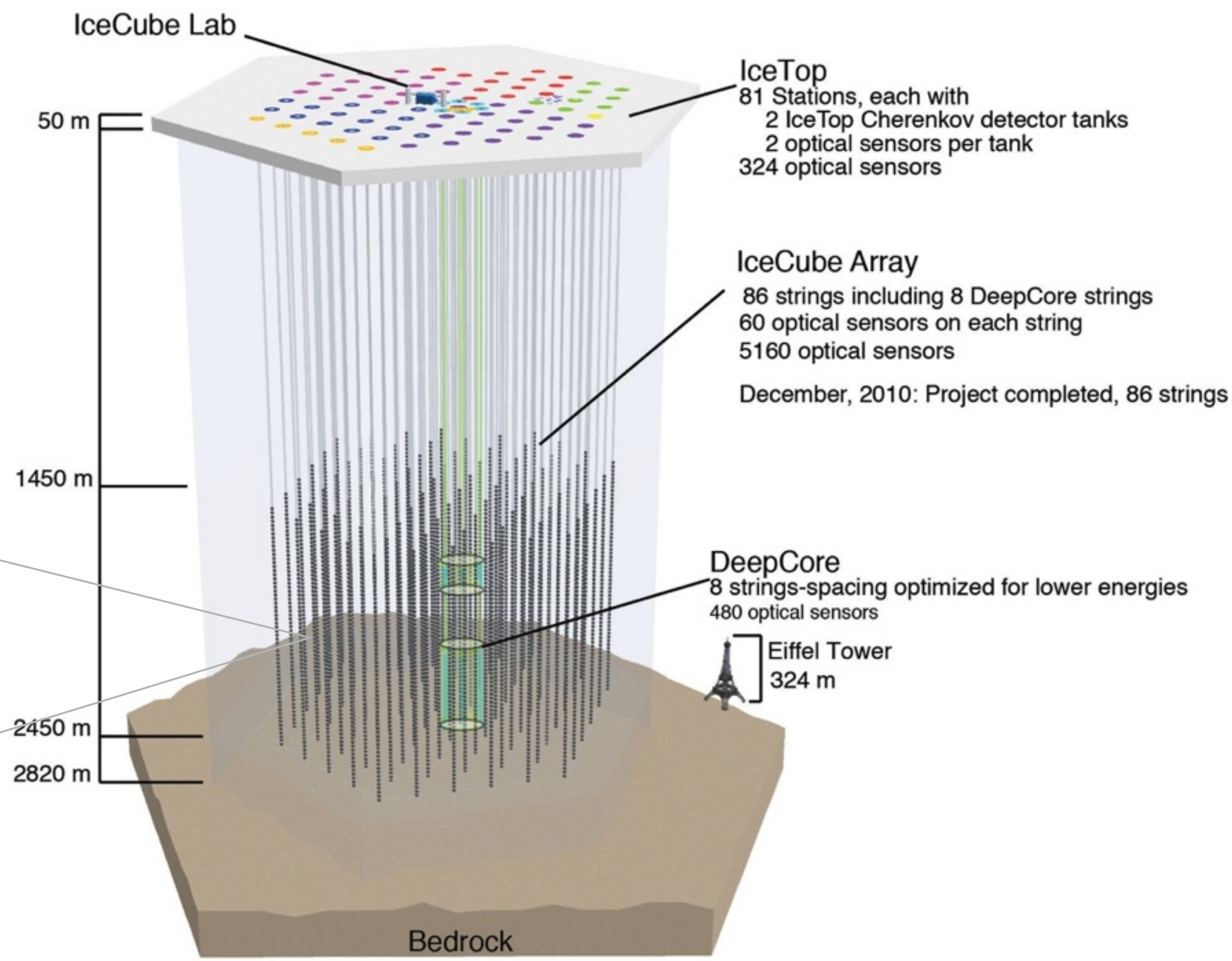
*Precision IceCube Next-Generation Upgrade

**Multi-megaton Ice Cherenkov Array

IceCube and DeepCore

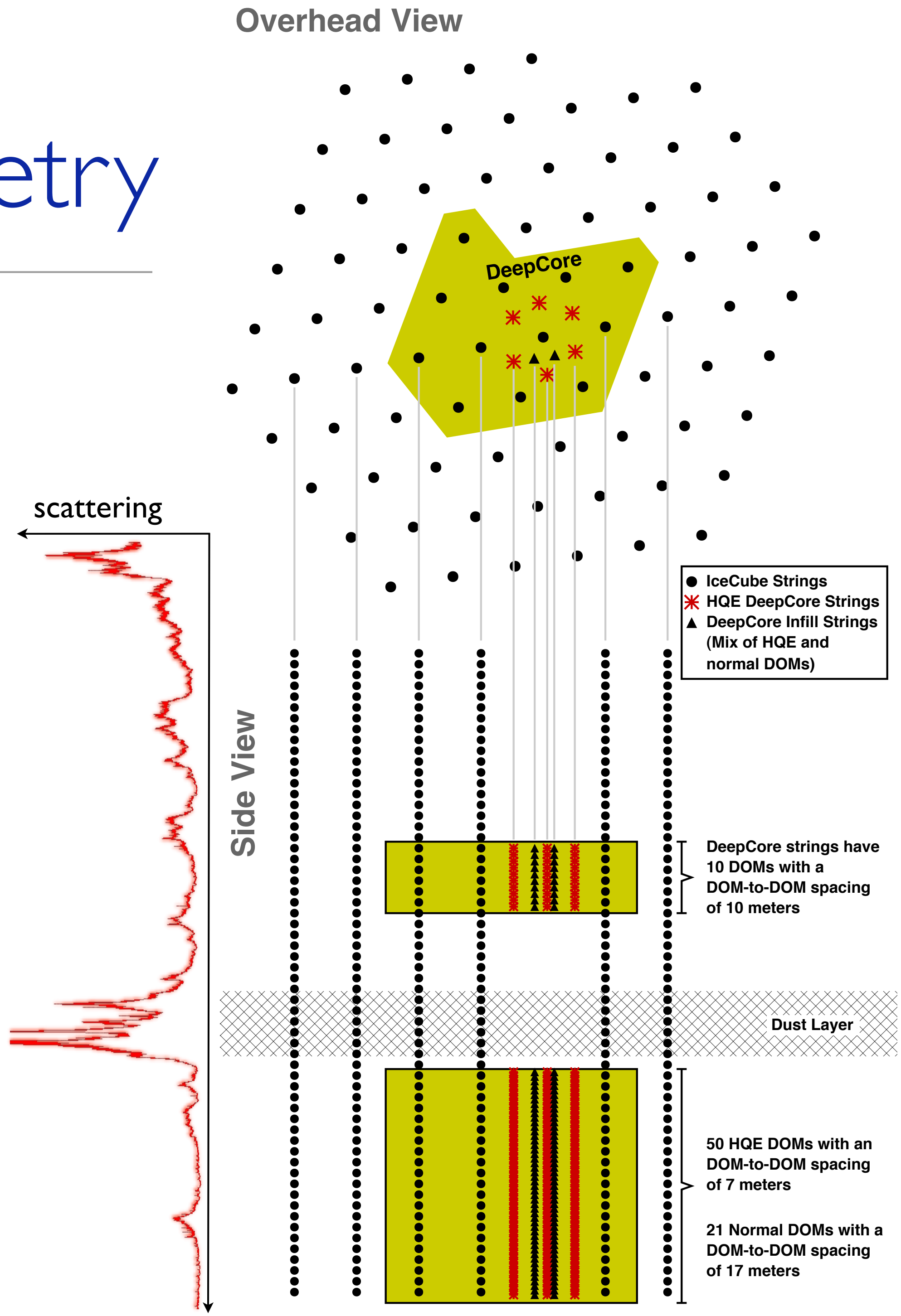


Digital Optical Module (DOM)



DeepCore Geometry

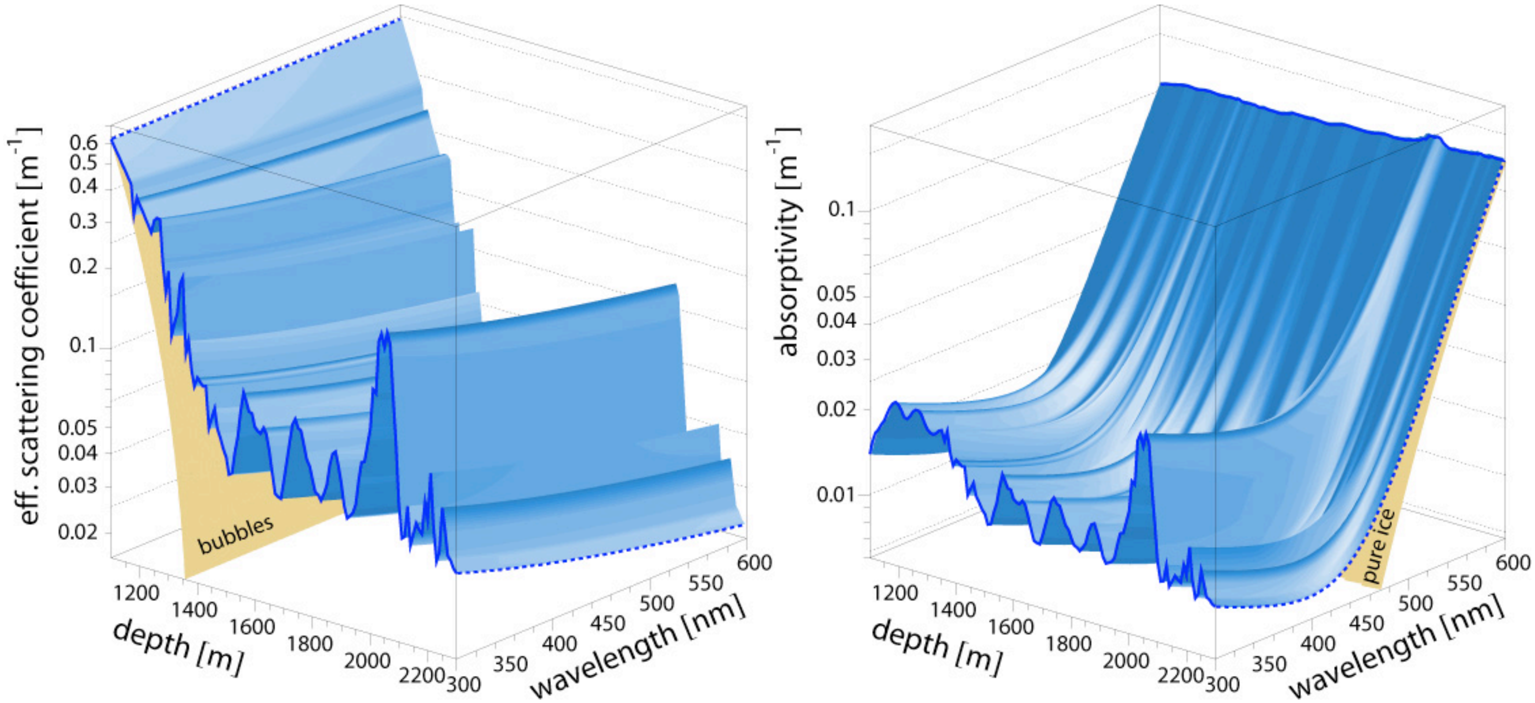
- Eight special strings plus 12 nearby standard IceCube strings
  - 72 m interstring horizontal spacing (six with 42 m spacing)
  - 7 m DOM vertical spacing
  - ~40% higher Q.E. PMTs
  - ~5x higher effective photocathode density (but still only ~0.1% coverage)
  - DOMs: ~1 ns timing, 0.25 p.e. threshold
- Roughly 30 MTon physical volume
  - ~10 GeV threshold
  - $\mathcal{O}$(200k) atmospheric ν/yr



Ice Properties

- Depth dependence of λ_{eff} and λ_{abs} from *in situ* LEDs

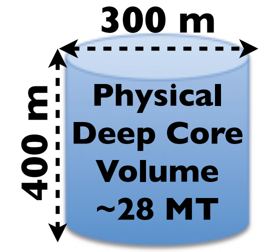
- Ice below 2100 m in DeepCore fiducial region <u>very</u> clear
  - $<\lambda_{eff}>$ ~ 47 m, $<\lambda_{abs}>$ ~ 155 m

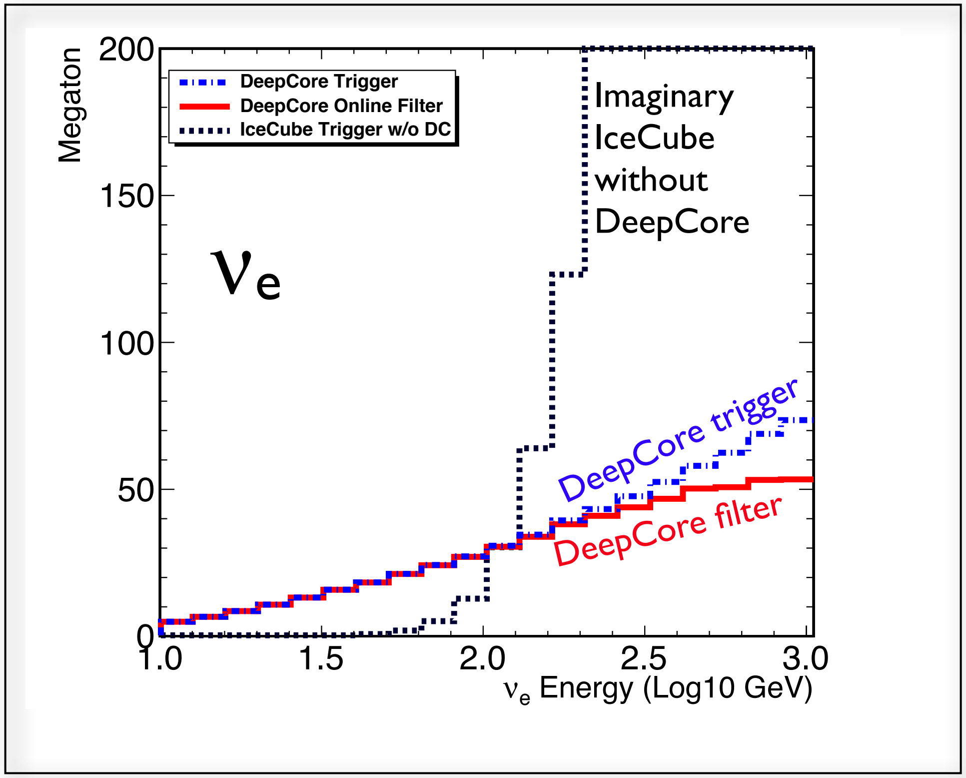


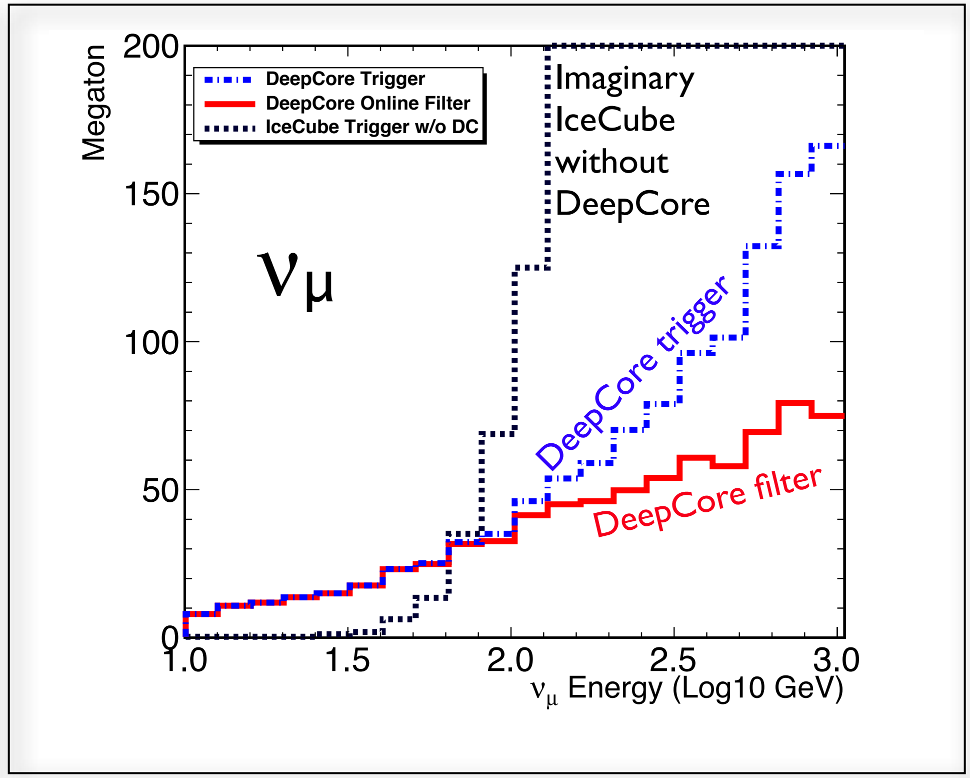
- Constant temperature ~ -35C

DeepCore: Effective Volume

$$V_{eff} = \frac{N_{acc}}{N_{gen}} V_{gen}$$





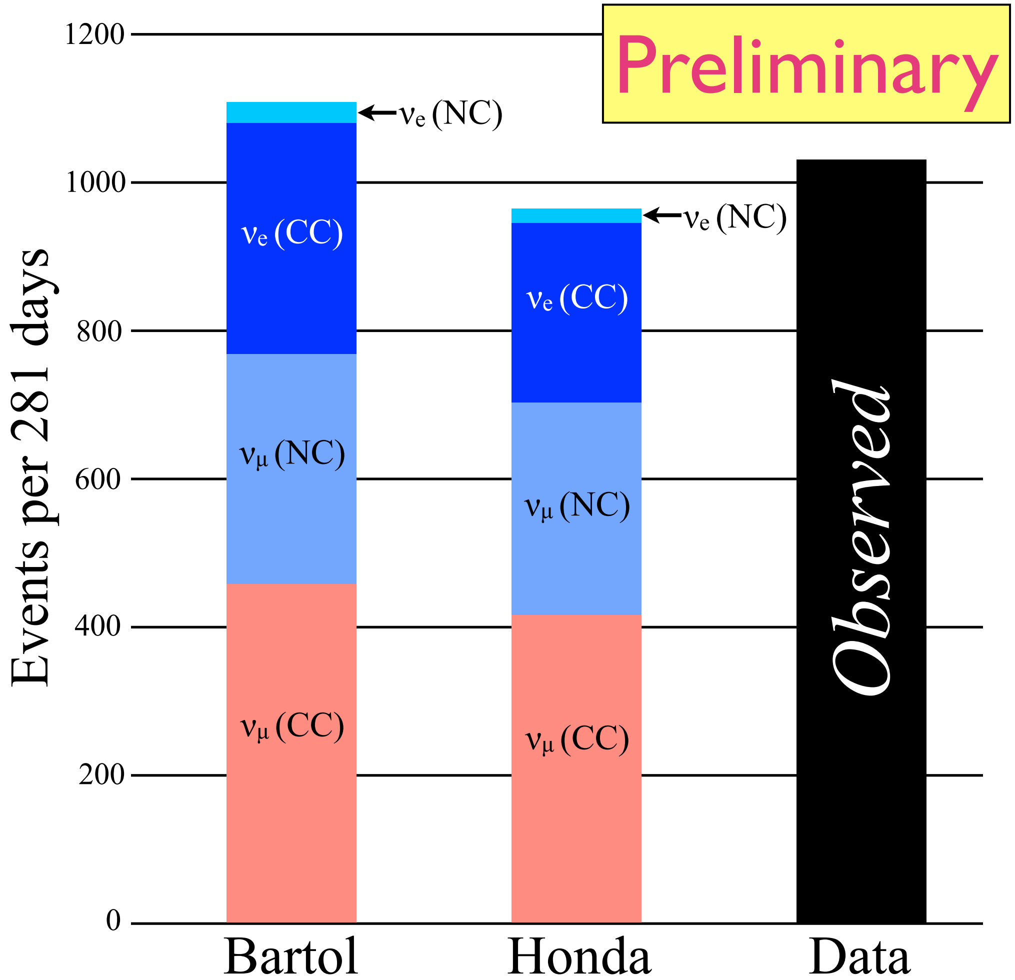


J. Koskinen/Penn State

- Many events in IceCube will also trigger DeepCore
  - These events are rejected by the online veto algorithm
- Below ~100 GeV, DeepCore improves V_{eff} significantly
- Final V_{eff} will be lower than shown once we require good event reconstruction

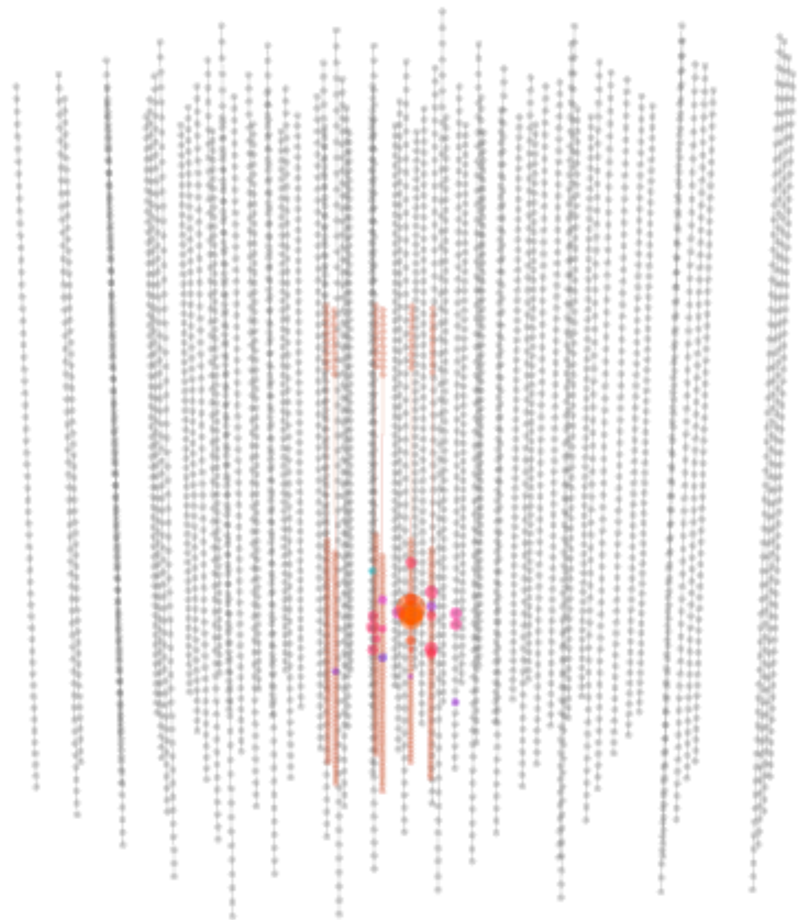
First Result from DeepCore

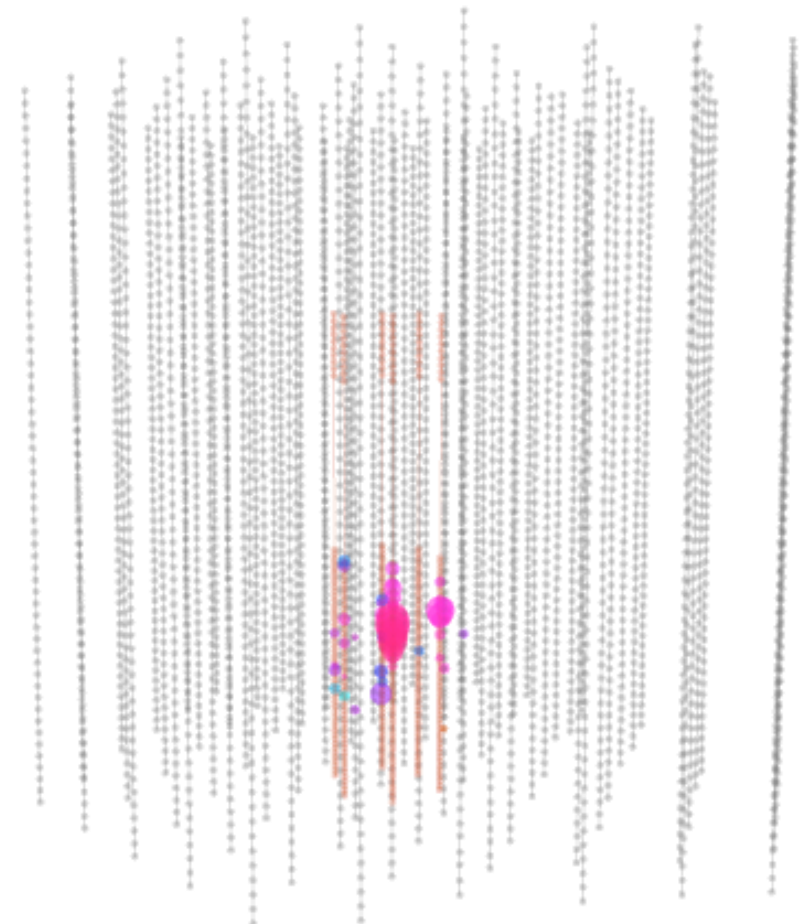
- Isolation of atmospheric ν-induced "cascade" sample (ν_e CC, ν_x NC)
- 1029 events:
  - 59% cascade
  - 41% ν_μ CC
- ~5x enrichment of cascade sig.: $[\text{casc/trk}]_{\text{veto}}$ / $[\text{casc/trk}]_{\text{final}}$ (without reconstructions)
- ~10^8 downward-going cosmic ray muon rejection factor
- Average energy: ~180 GeV
- Paper being written
- Loosening cuts: see $\nu_\mu \rightarrow \nu_\tau$ a la SK?



First Result from DeepCore

Two candidate events



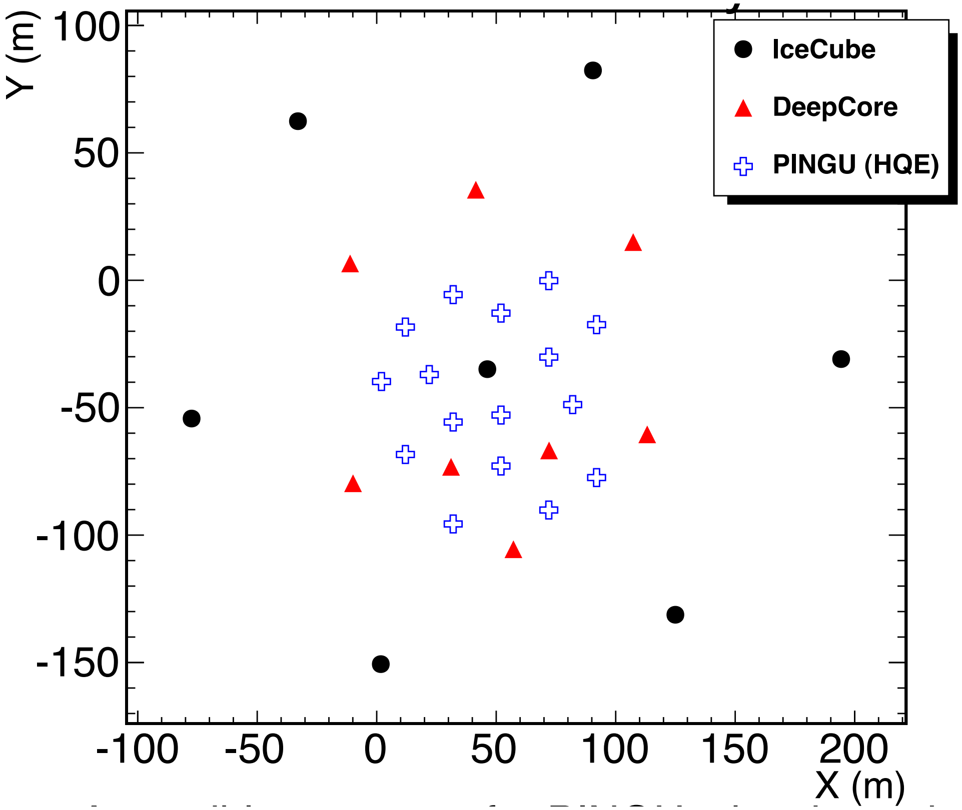


(Standard hit cleaning algorithm removed all noise hits in rest of detector.)

The Next Step: PINGU

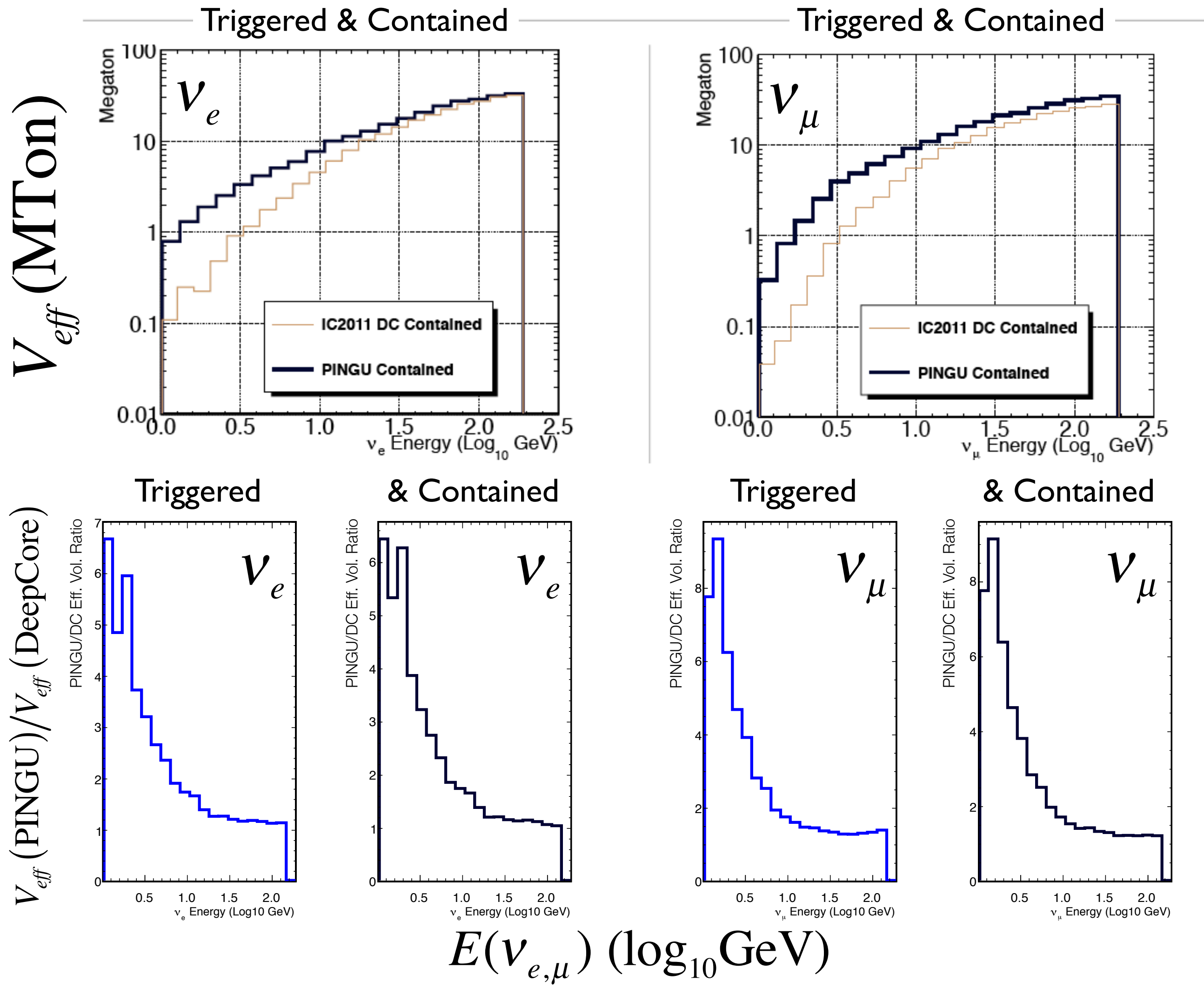
- Further increase sensor density
  - ~20 additional strings
    - Mostly IceCube technology plus some R&D modules
    - Include new low-E calibration devices
  - Aims:
    - Physics program at E_{thr} ~ few GeV
    - R&D: Cherenkov ring segment reconstruction
    - Calibrate for light levels at E ~ 1 GeV
- Collaboration
  - IceCube +, U.M.-Duluth, U. Erlangen, T.U.-Muenchen, NIKHEF, U. Wuerzburg
  - 2nd workshop early January, regular conference calls, wiki, listserv

Example PINGU Geometry



PINGU Effective Volumes

- V_{eff} increased by ~8x at ~1 GeV relative to DeepCore



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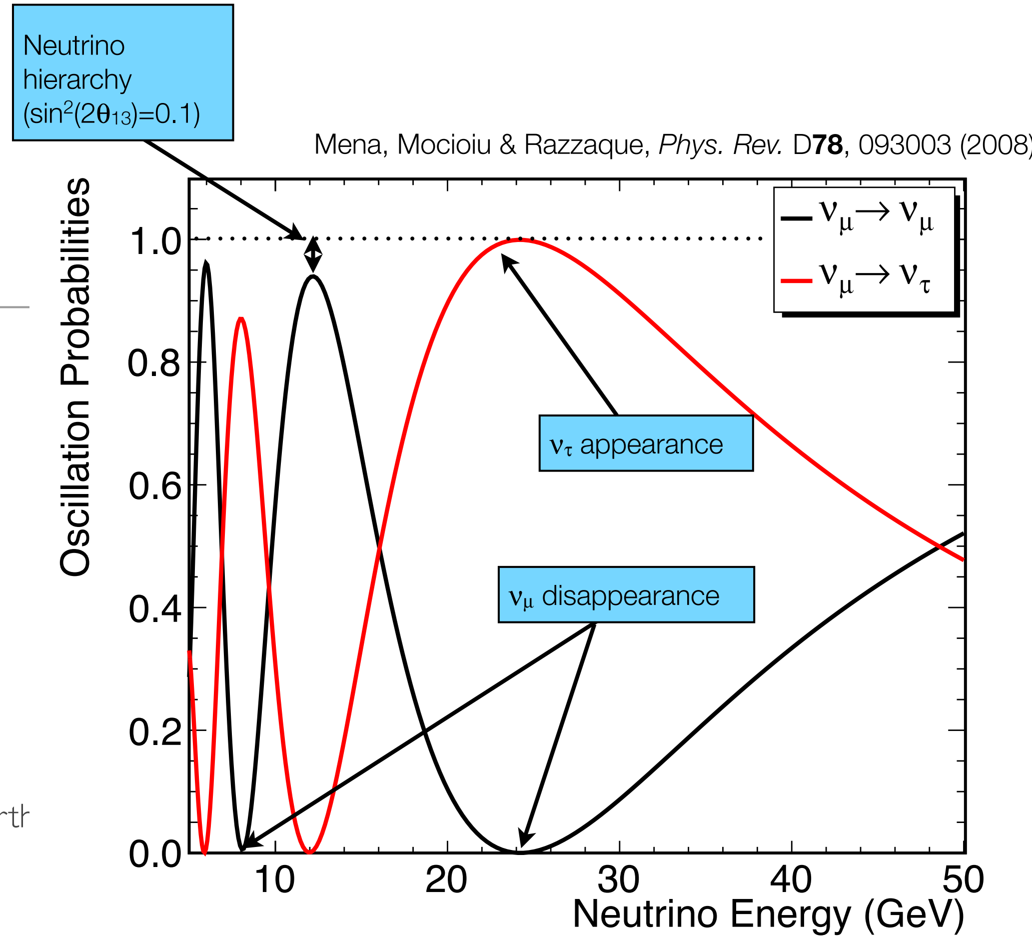
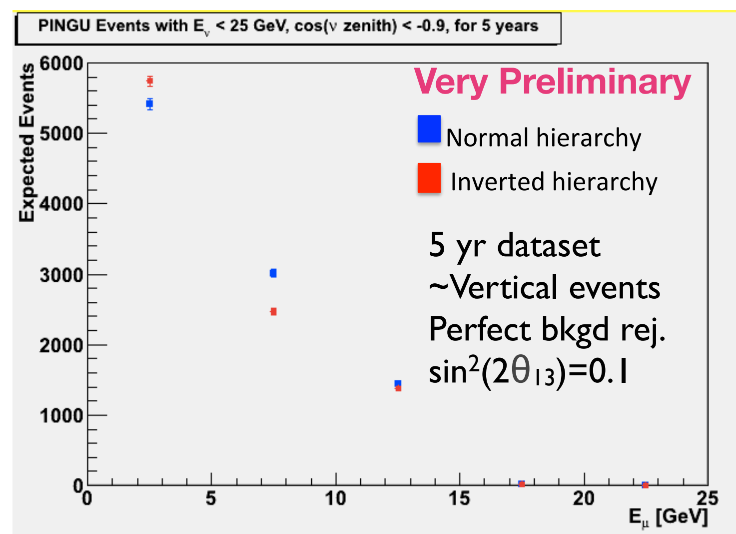
"Triggered": Event satisfies trigger condition of 3 neighboring hits within 1μs.

"Contained": Event's true vertex is within fiducial volume.

PINGU Physics

- Gain sensitivity to E(ν) < ~5 GeV
  - Second trough: pin down $(\Delta m_{23})^2$
  - Neutrino hierarchy? Plausible:
    - exploit asymmetries in the nu/anti-nu σ's; kinematics
    - Effect largest at E(ν)<5 GeV, r=d_{Earth}
    - Nature may be kind and provide a sufficiently large θ_{13}
    - Control of systematics is key
- Probe lower mass WIMPs
- Extensive calibration program
- Pathfinder technological R&D for MICA

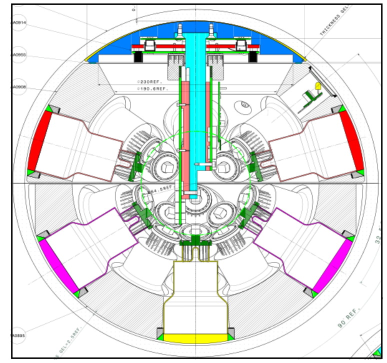




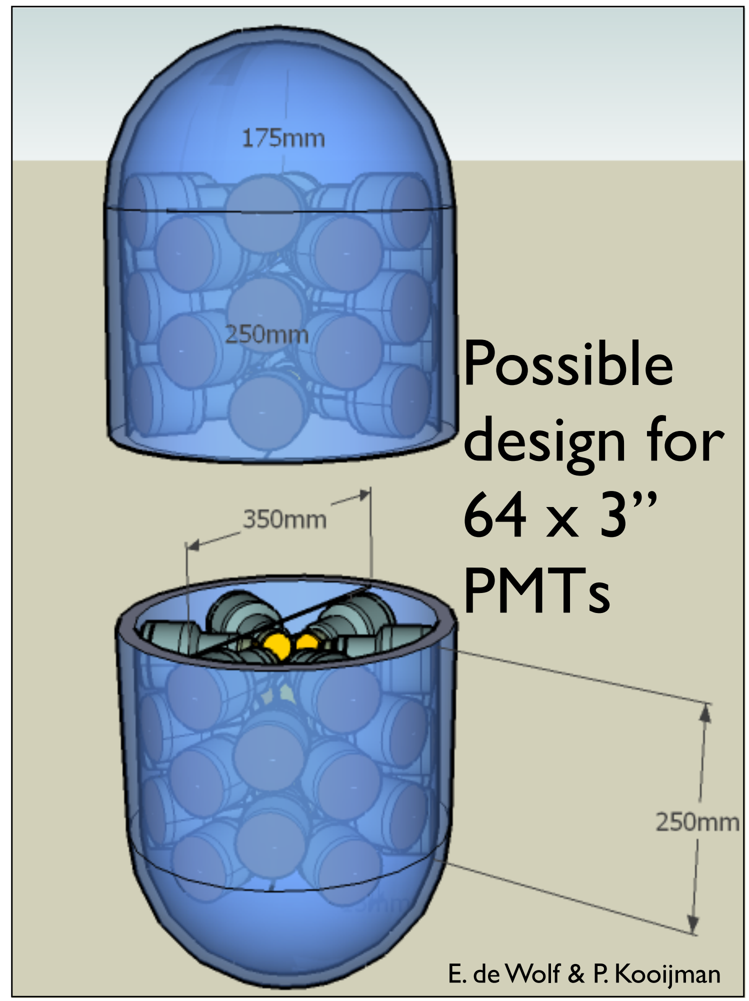
D. Grant/U. Alberta

PINGU R&D:
Composite Digital Optical Module

- Cylinder with 64 3" PMTs and electronics; single connector
  - Effective photocathode area >6x that of a 10" PMT
  - Diameter comparable to IceCube DOM so drilling requirement would be similar
  - Design study underway (NIKHEF, Erlangen)
- Cherenkov ring imaging in the ice
  - Connect "stripes" of rings
- Wavelength shifter and other technologies also under exploration




Existing KM3NeT Design



P. Kooijman, NIM A567 (2006), S. Kuch NIM A567 (2006), KM3NeT TDR

MICA: Towards a Multi-MTon MeV-GeV Detector in the Ice

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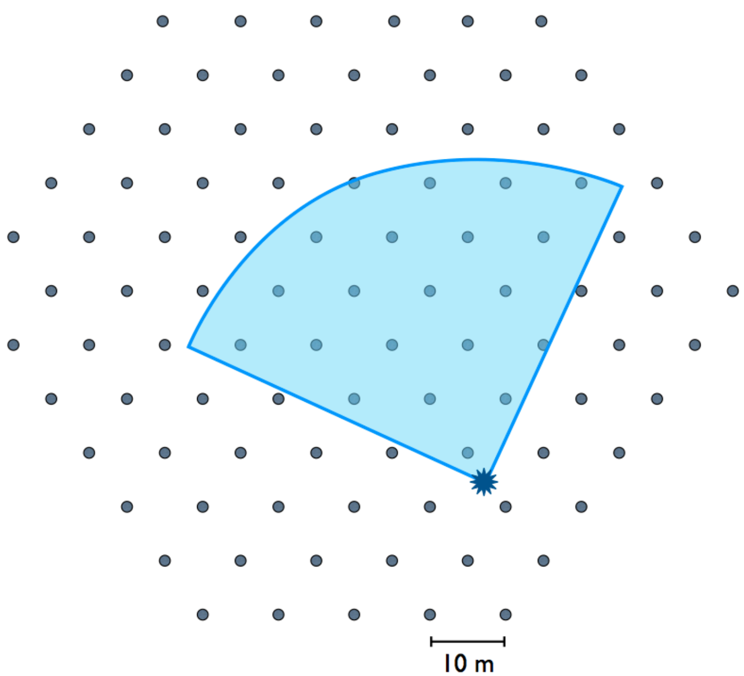
- We present here *plausibility* arguments
  - Physics:
    - Adequate % photocathode area for Cherenkov ring imaging may be attainable
    - Assume Cherenkov ring reconstruction algorithms for detector with modules *in fiducial volume* are feasible
  - Construction, Logistics, Schedule:
    - IceCube has demonstrated high-speed hot water drill capable of 20 holes per season; managed challenging South Pole logistics
  - Cost: Detection medium is the support structure
    - Driver is photocathode, not civil engineering
- Fundamental question: How much information can we extract from the ice?
  - Simulations underway, studying signatures of
    - supernova neutrino bursts with ~20 MeV neutrinos
    - proton decay ($p \rightarrow \pi^0 e^+$)

MICA: Photocathode Coverage

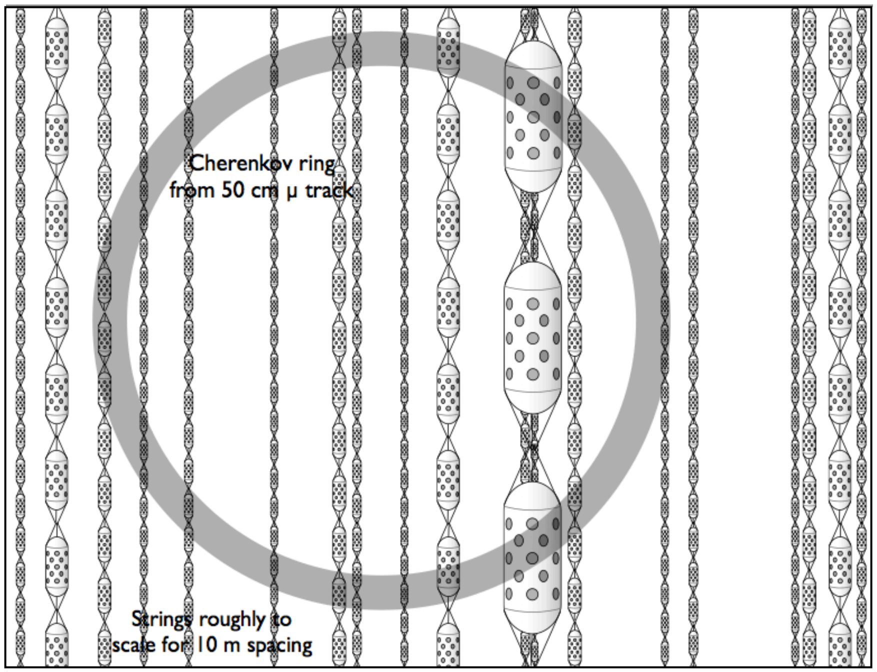
- Back-of-the-envelope sub-optimal strawman using existing technology, IceCube-scale effort (~7 yrs) & expense (~$300M):
  - 120 IceCube 10" PMT DOMs on 60 strings
  - 3 m vertical DOM spacing
  - 5 m horizontal string spacing
  - r = 50 m cylindrical geometry
  - encloses ~3 MTon of ice
- Gives ~1.5% photocathode coverage
  - with composite DOMs: ~4%
- These numbers can be improved by
  - Optimizing geometry
  - Adding more photon detection units

MICA: Toy Geometry

~100 strings, ~300 modules/string

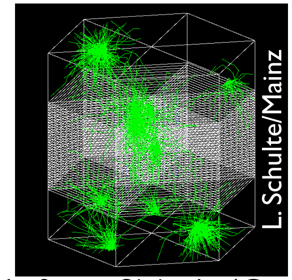


Top view



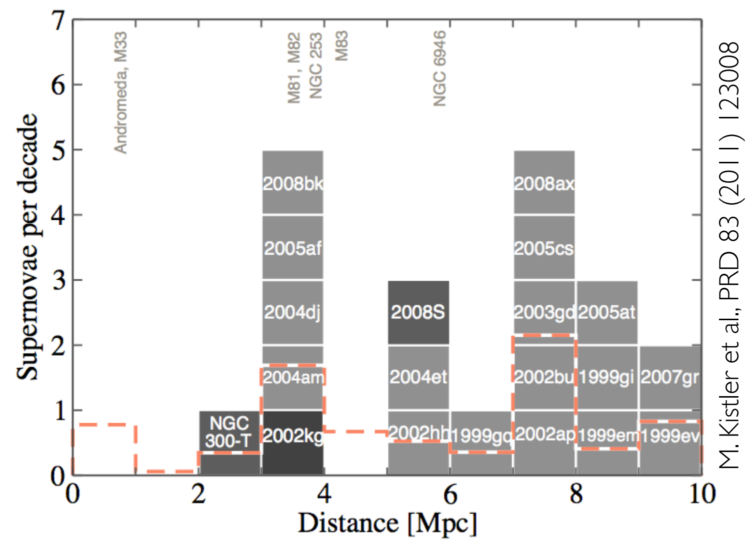
Side view

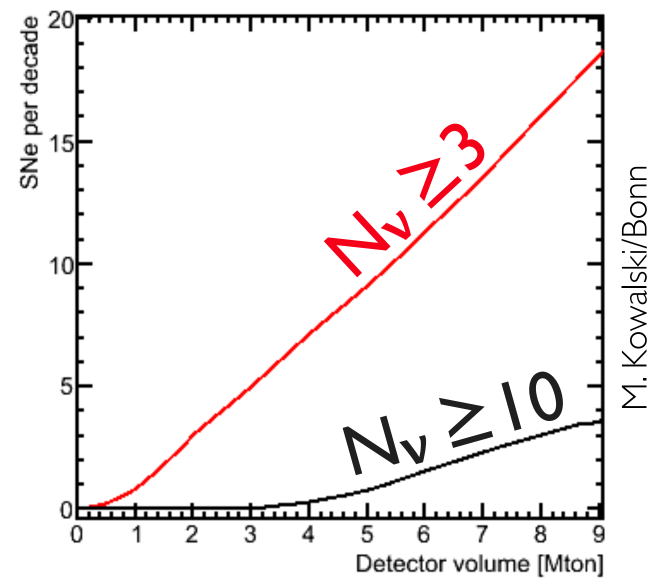
MICA: Supernovae



γ's from SN ν's (Geant4)

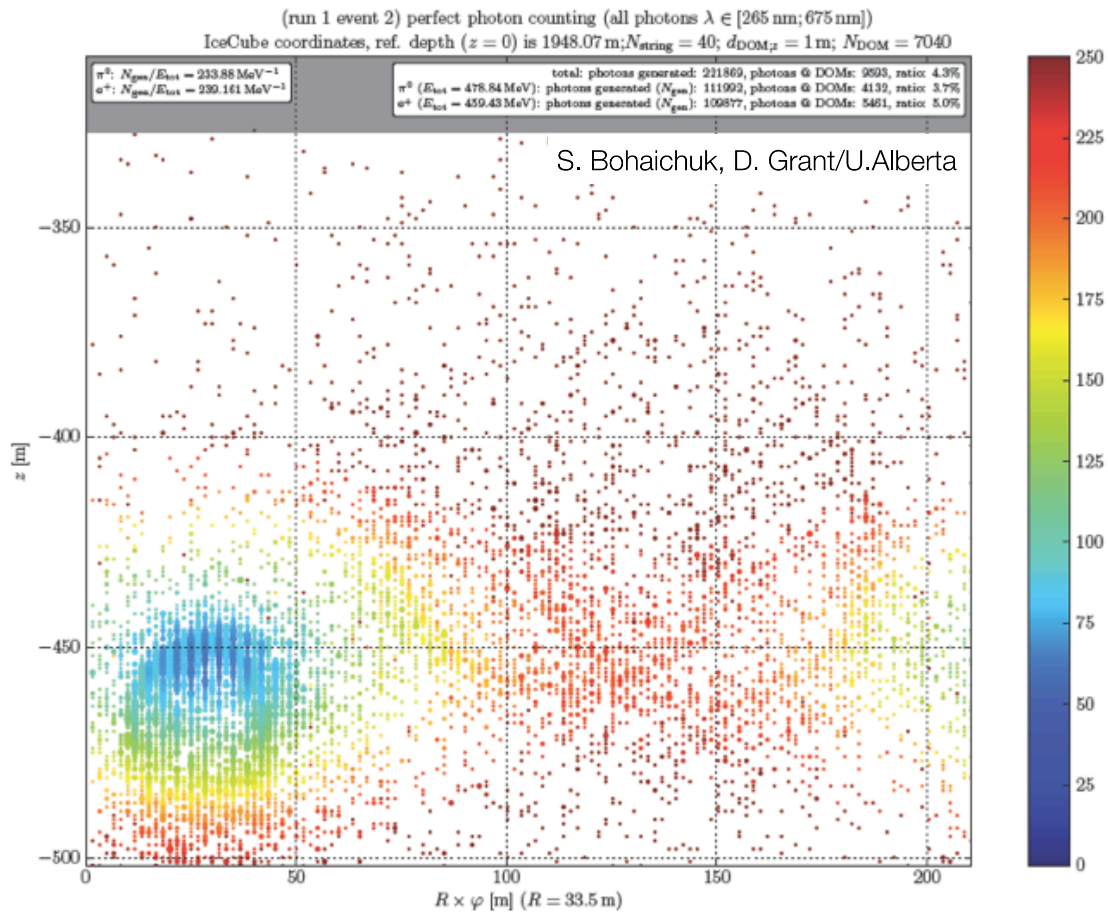
- SN neutrinos at 10-20 MeV would produce 2000-4000 Cherenkov photons:
  - Even few percent photocathode coverage enough to see a single SN neutrino
  - A burst of >=3 neutrinos in 1-10s would be above atmospheric neutrino background
    - Have not yet looked at spallation daughters
  - A ~5 MTon detector could see to ~10Mpc
    - Roughly annual supernova neutrino detection!
  - Other benefits:
    - Early triggers for optical telescopes
    - ...and gravitational wave detectors: bkgd. reduction ~10^6 ; signal enhancement ~1000x
  - Caveats: LOTS of uncertainties (reconstruction, particle ID, spallation rejection...)





MICA: Proton Decay

- Very challenging. To beat backgrounds from atmospheric neutrinos and muon spallation products one needs:
  - energy (momentum) resolution
  - particle ID via Cherenkov ring reconstruction
  - high photocathode area
- Simulations just starting



$p \rightarrow \pi^0 + e^+$

Idealized

1.5 MTon (5×10^{35} protons),
10 MeV threshold,
240 photons/MeV,
5% photons detected,
NO scattering

PINGU and MICA: Possible Timeline

PINGU

March 2011 — 1st PINGU workshop - NIKHEF

Fall 2012 — Begin simulation studies for 18-20 string detector with threshold ~1GeV. Targeted Physics: WIMPs, neutrino oscillations, SN

Submit Letter of Interest to NSF

Jan 2012 — 2nd PINGU workshop - Penn State

Spring 2012 — Complete 1st DC analyses. Establish R&D plans as part of PINGU

Summer 2012 — Submit PINGU Proposal

Winter 2014/15 — Begin deploying PINGU

Winter 2015/16 — Finish deploying PINGU including R&D strings

MICA

Fall 2012 — Complete initial simulation feasibility studies

Fall 2012 — R&D proposals to Agencies

Spring/Fall 2016 — Submit proposals to Agencies

Winter 2018/19 — Start deployment

Spring 2021 — Begin data analysis

Conclusions

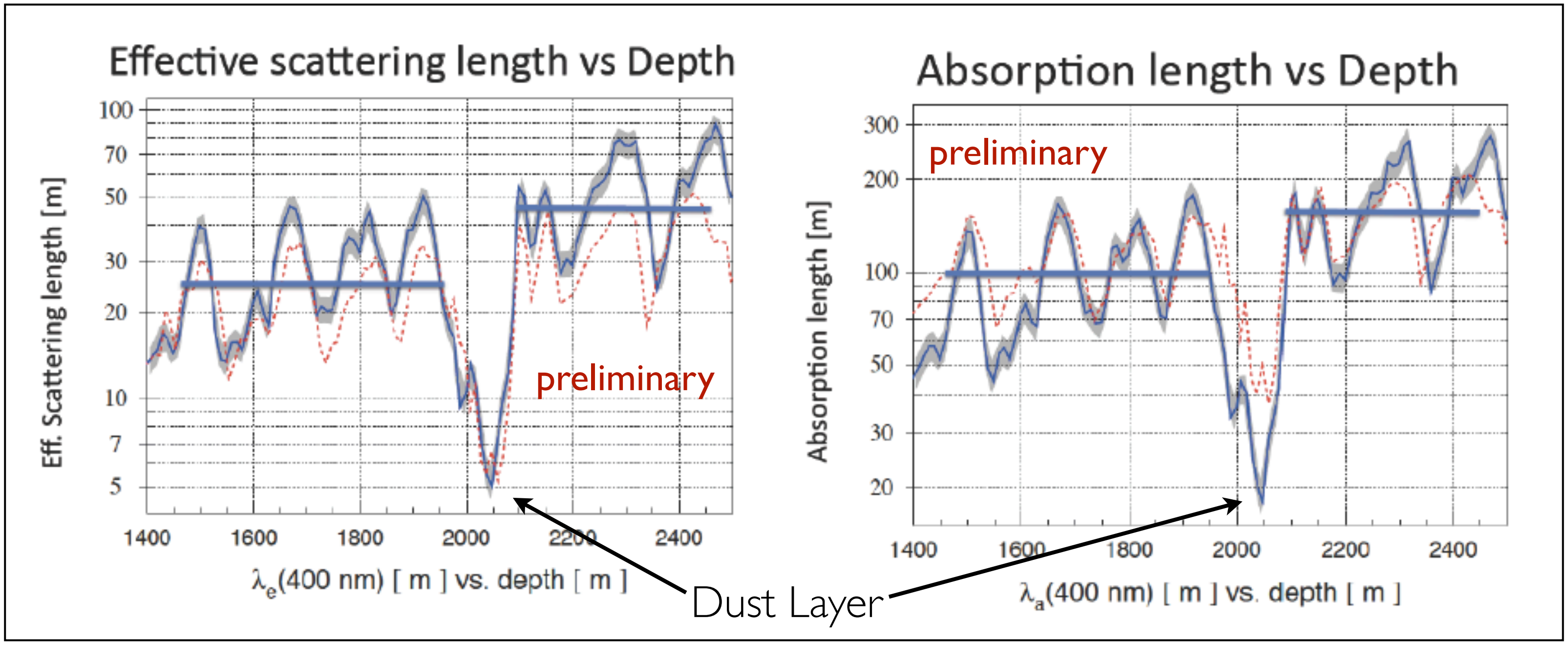
- DeepCore has much promise at the 10-100 GeV scale
  - atmospheric neutrinos, oscillations
  - WIMP dark matter
  - southern sky sources, exotica,...
- PINGU could reach to a few GeV
  - improve on many DeepCore measurements, perhaps measure hierarchy
  - perform R&D for MICA
  - New members welcome!
- MICA
  - Initial studies indicate plausibility for multi-MTon detector at MeV-GeV scale in ice
    - Informed by IceCube construction experience
    - Favorable cost profile
    - Benefits from existing IceCube/DeepCore/PINGU detectors and associated infrastructure
  - Detailed MC studies underway for SN neutrinos and proton decay
  - New members welcome!

The End

Backup slides follow

Ice Properties

- Depth dependence of λ_{eff} and λ_{abs} from *in situ* LEDs
- Ice below 2100 m in DeepCore fiducial region very clear
  - $<\lambda_{eff}> \sim 47$ m, $<\lambda_{abs}> \sim 155$ m

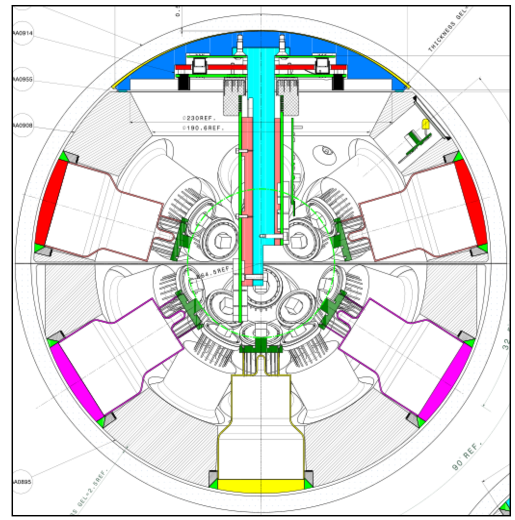


- Constant temperature ~ -35C

PINGU R&D:
Composite Digital Optical Module

Courtesy E. de Wolf & P. Kooijman

- Based on a KM3NeT proposed design (NIKHEF)
  - Glass sphere containing 31 3" PMTs and associated electronics
    - Effective photocathode area 4x that of standard 8" PMT, but
      - with better granularity
      - hopefully lower cost/area
  - Single connector keeps deployment simple

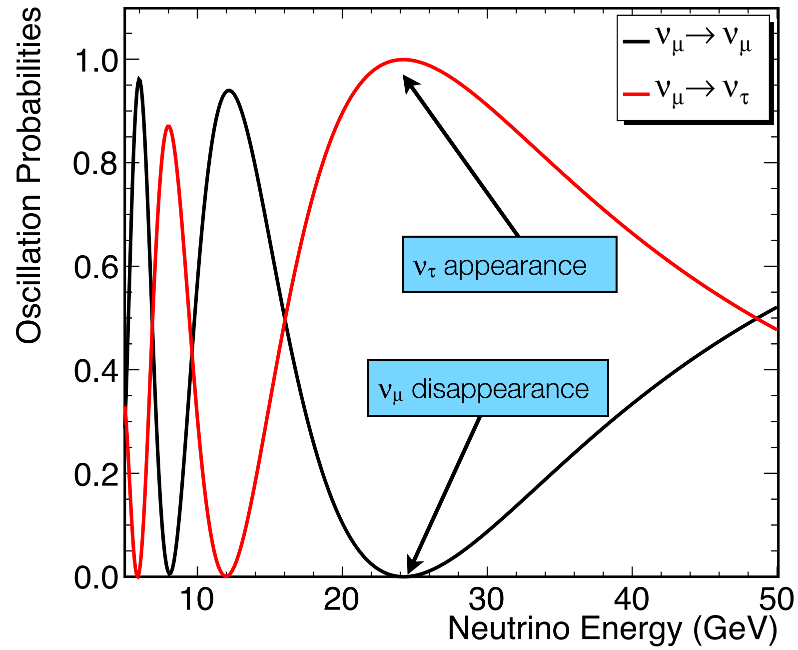


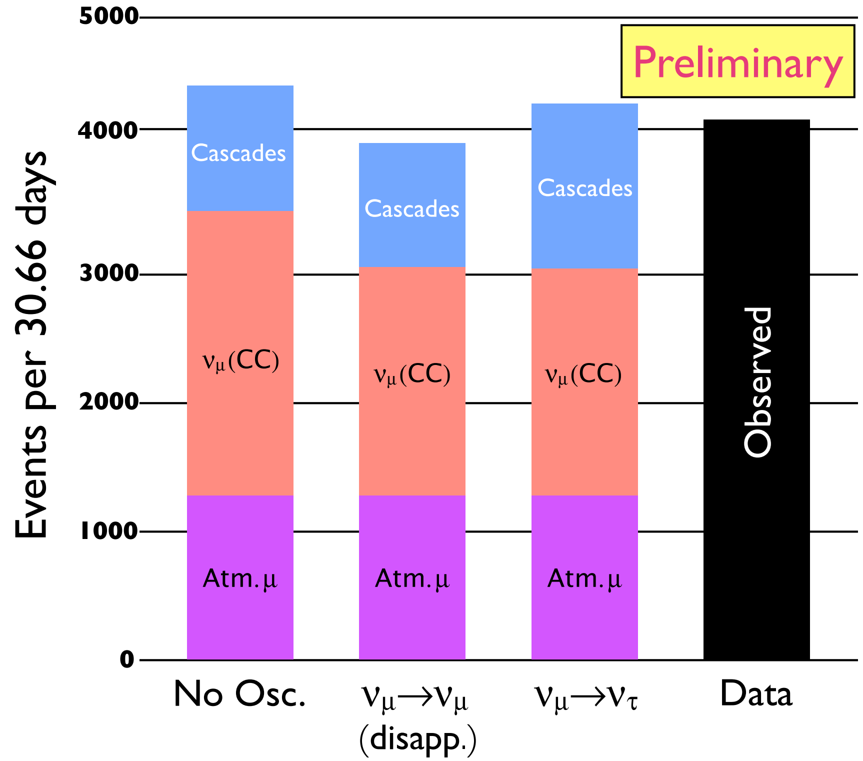
P. Kooijman, NIM A567 (2006), S. Kuch NIM A567 (2006), KM3NeT TDR

Next(?) Result from DeepCore

- Loosen cuts for possible sensitivity to $\nu_\mu \rightarrow \nu_\tau$ oscillations
- <u>Lots</u> of statistics
  - >10x more data in hand
  - Key: control of systematics
- Similar to SuperK measurement
  - PRL 97:171801 (2006)

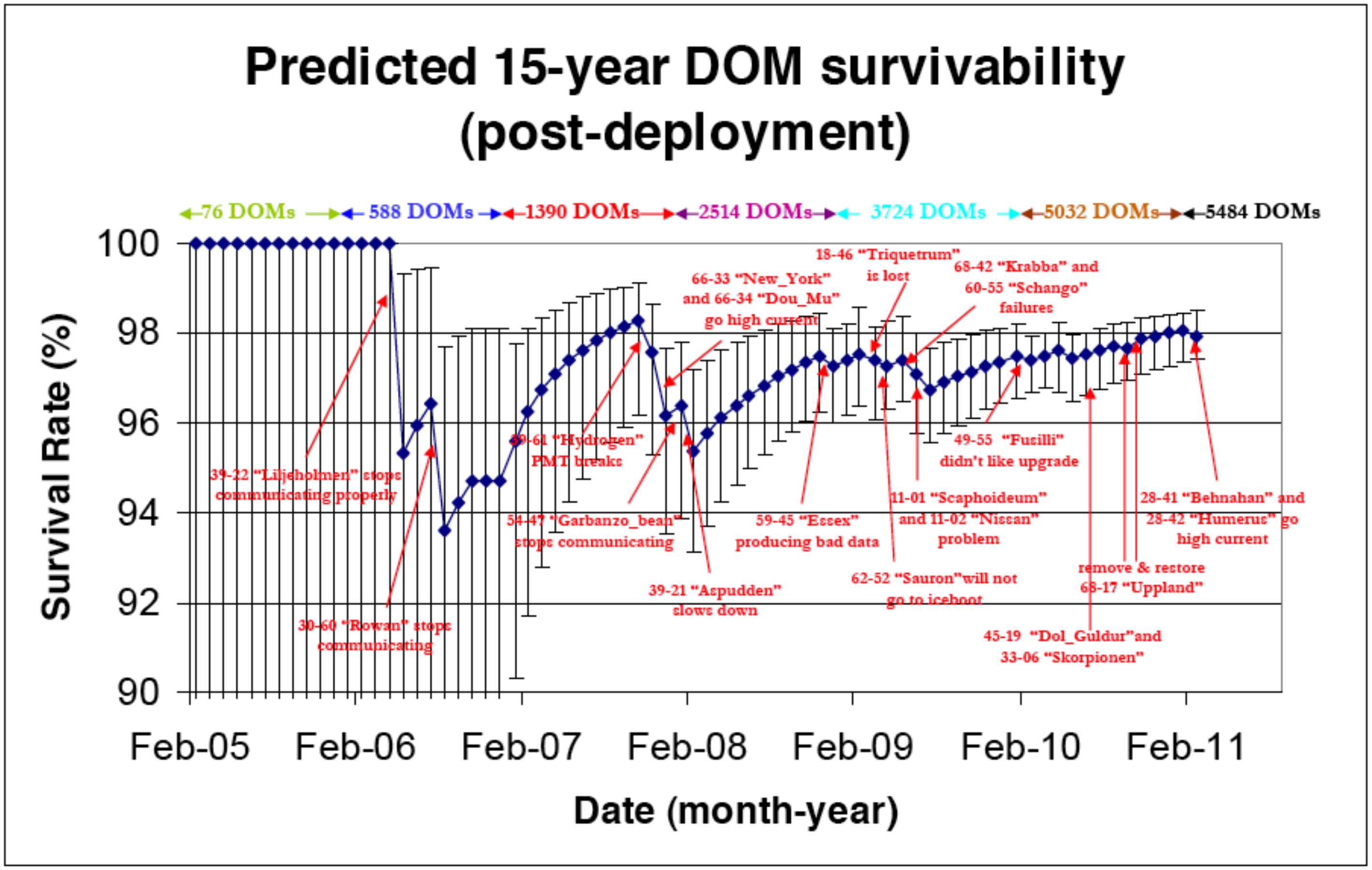
Mena, Mocioiu & Razzaque, *Phys. Rev.* D**78**, 093003 (2008)





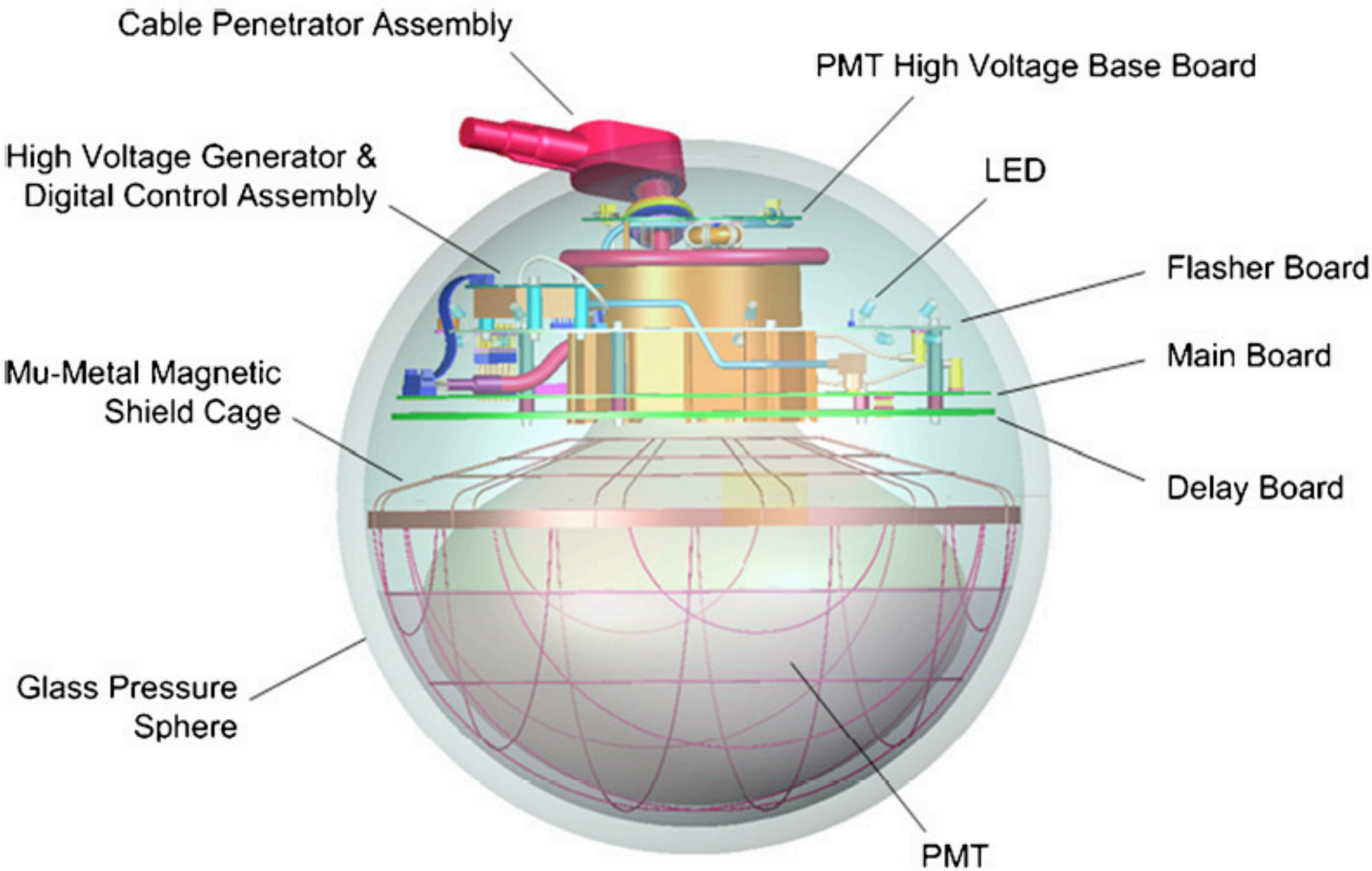
DOM Reliability

- 14k years total live-time
- 84 infant mortalities
- 19 lost thereafter



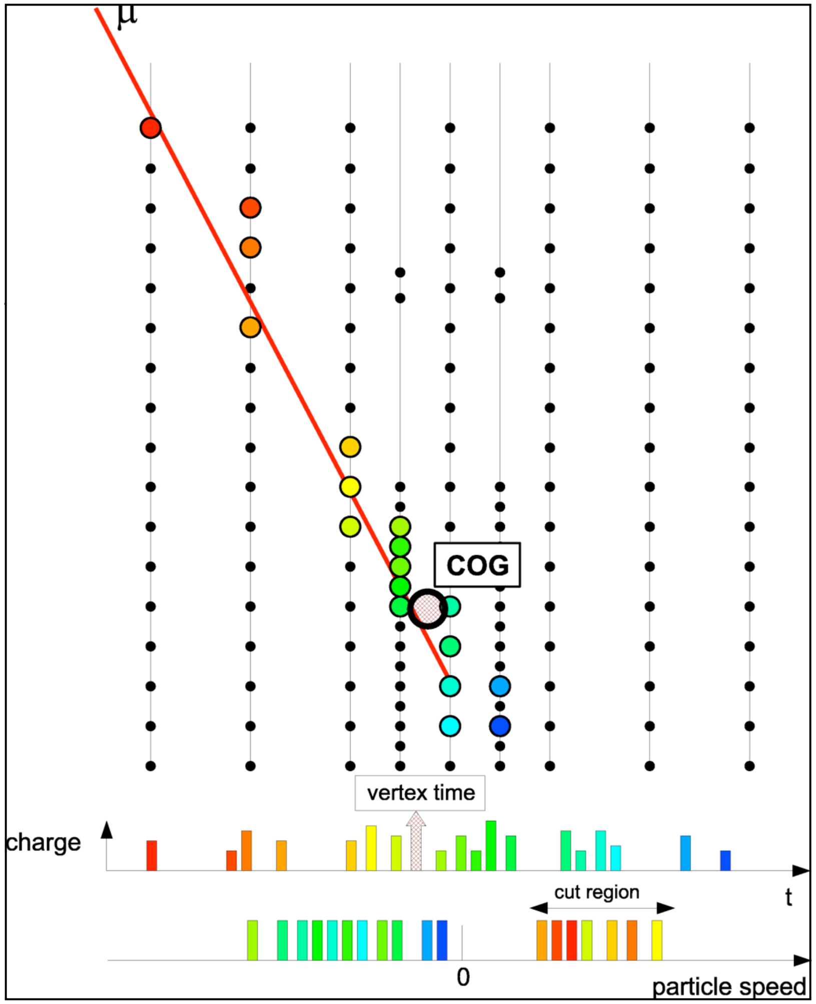
- Ice is a nice environment!

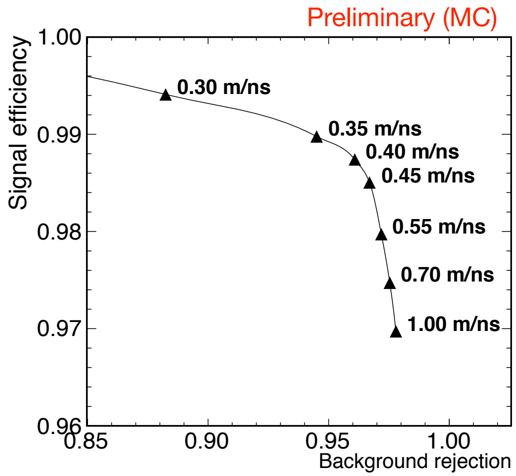
The Digital Optical Module (DOM)



DeepCore: Atmospheric Muon Online Filter

- First, trigger on 3 or more hits in DeepCore fiducial volume in 2.5μs (“SMT3”)
- Then, look for hits in veto region consistent with speed-of-light travel time to hits in DeepCore
    - Achieves >2 orders of magnitude rejection of cosmic ray muons
    - Loss of <2% of fiducial neutrinos



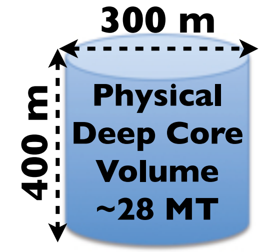


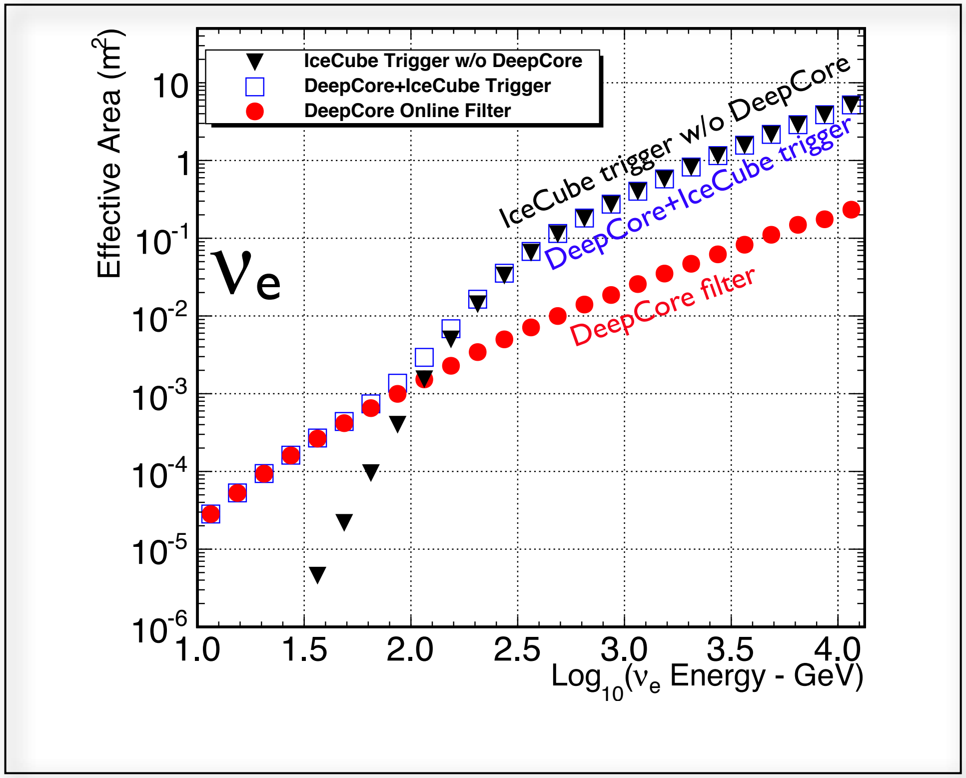
Require speed to be between 0.25-0.40 m/ns.

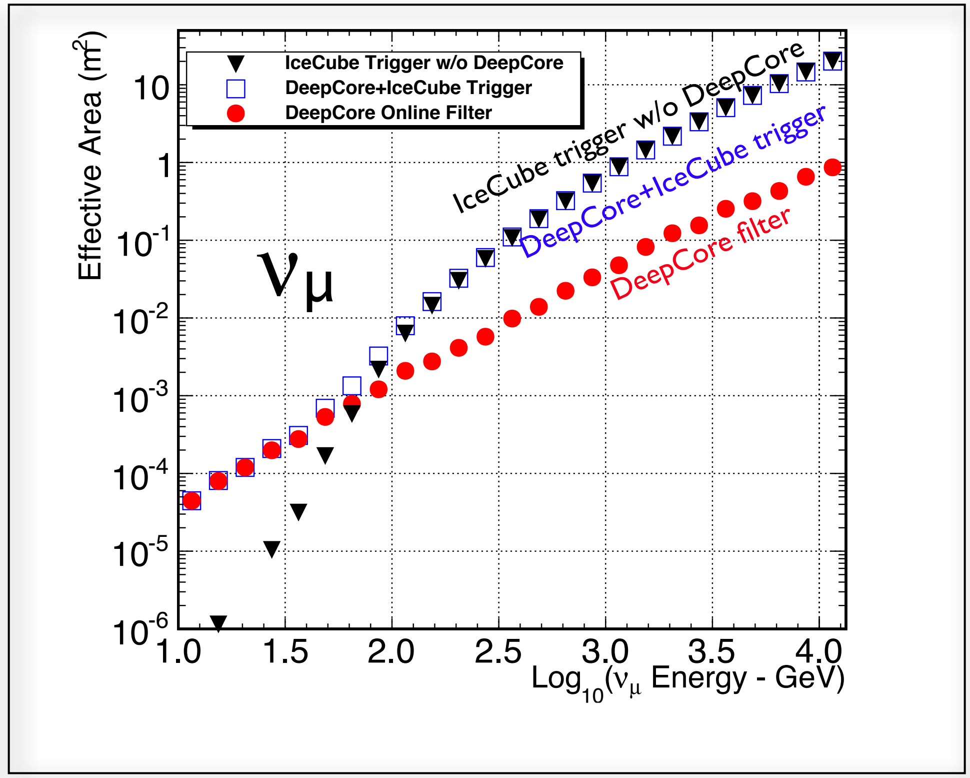
The value “0.40” was chosen by holding 0.25 constant and varying upper value, giving plot on left. (And similarly for 0.25.)

DeepCore: Neutrino Effective Area

$$A_{eff} = \frac{N_{acc}}{N_{gen}} A_{gen}$$





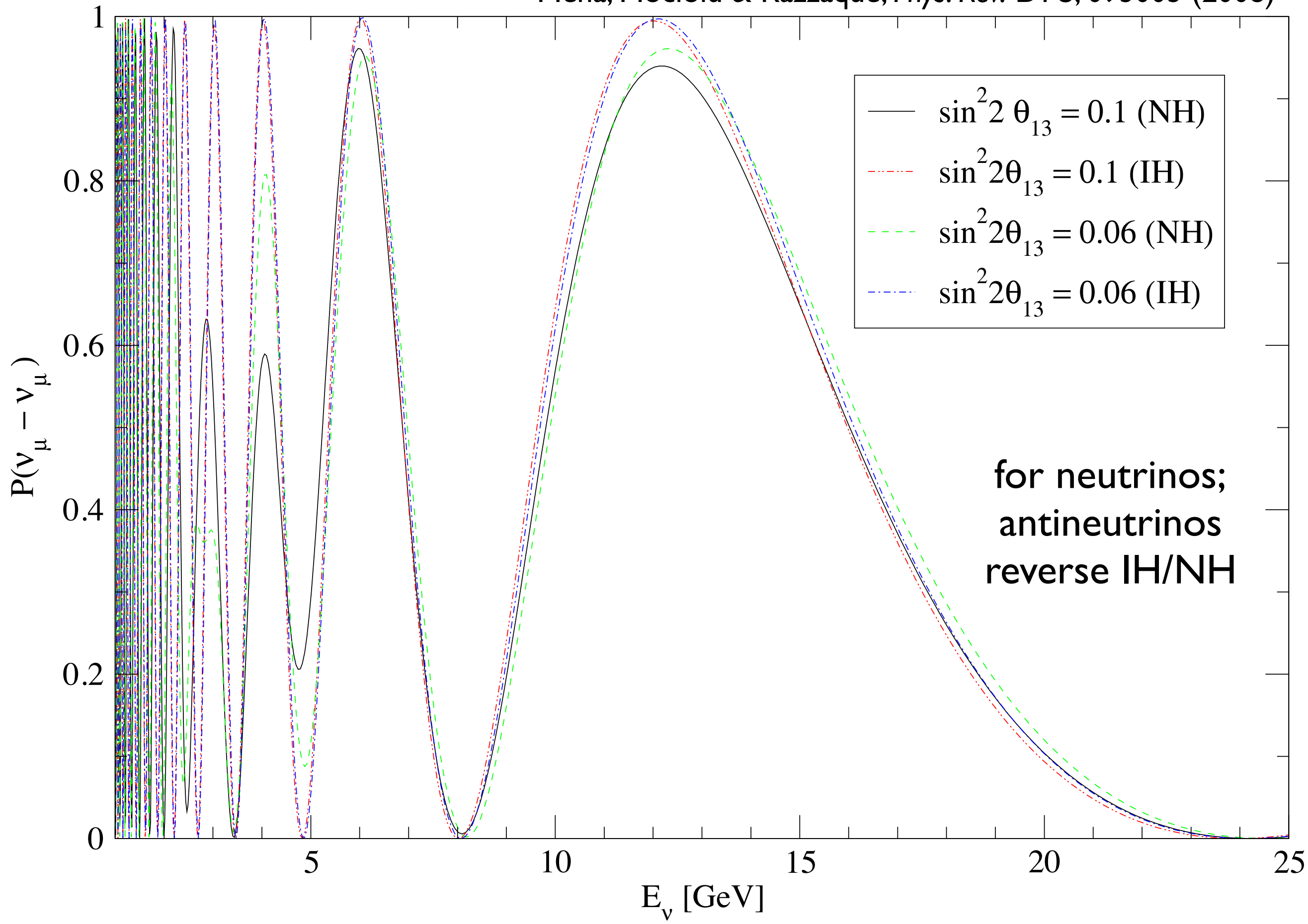


- Below ~100 GeV, DeepCore improves A_{eff} significantly
  - Improved trigger efficiency of DeepCore overcomes its smaller volume relative to IceCube
  - Linear growth in A_{eff} is due to neutrino cross section, not detector efficiency
- Final A_{eff} will be lower than shown once we require good event reconstruction

Neutrino Mass Hierarchy

- For large θ_{13}, we might be able to exploit matter effects and ν-$\bar{\nu}$ asymmetries in $\sigma_{\nu N}$ and y to determine the hierarchy
- Very speculative, and relies on large θ_{13}, but it got us thinking about ways to go to even lower energy

Mena, Mocioiu & Razzaque, *Phys. Rev.* D78, 093003 (2008)

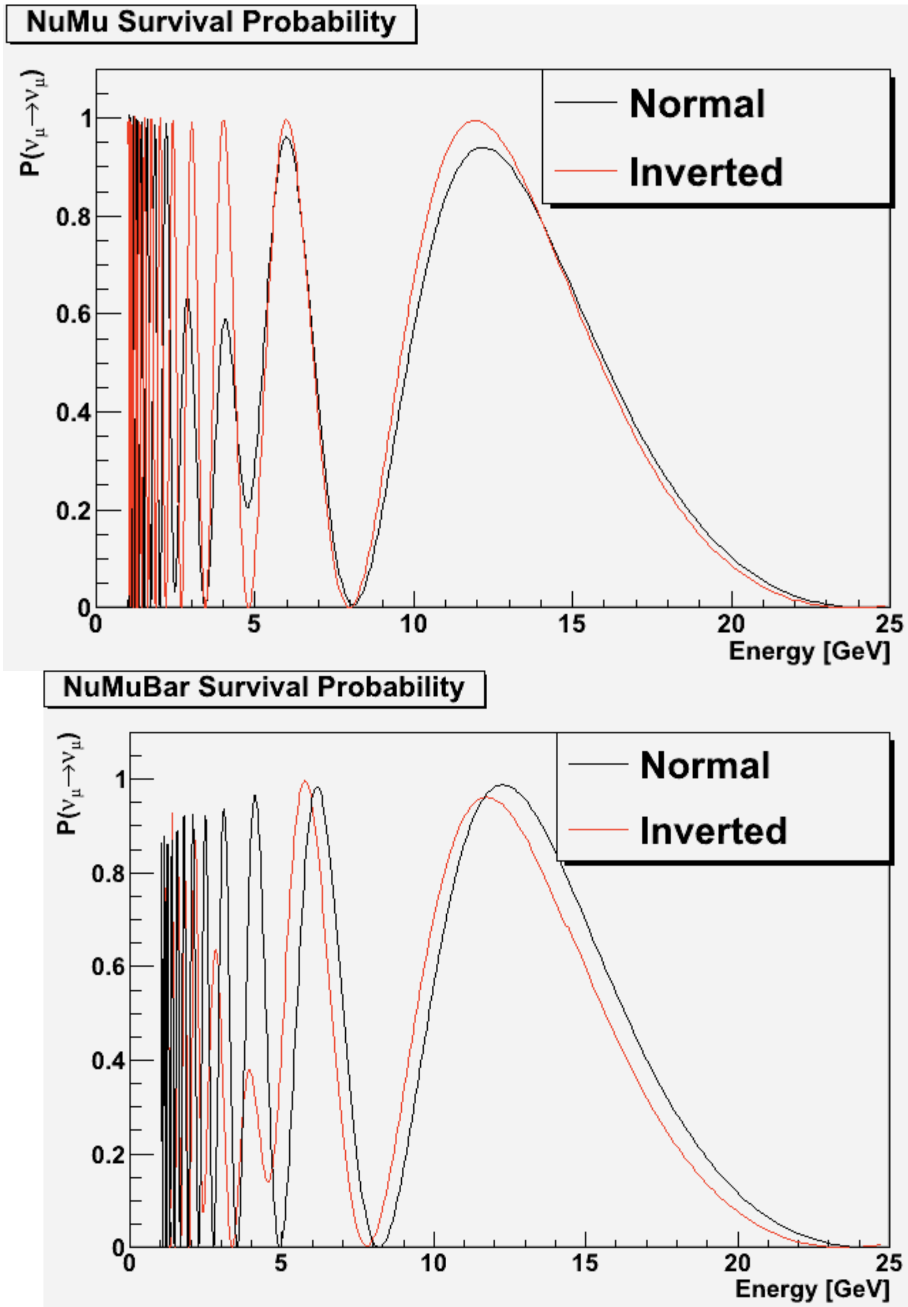


PINGU Neutrino Mass Hierarchy

Possible sensitivity to neutrino mass hierarchy via matter effects if θ_{13} is large

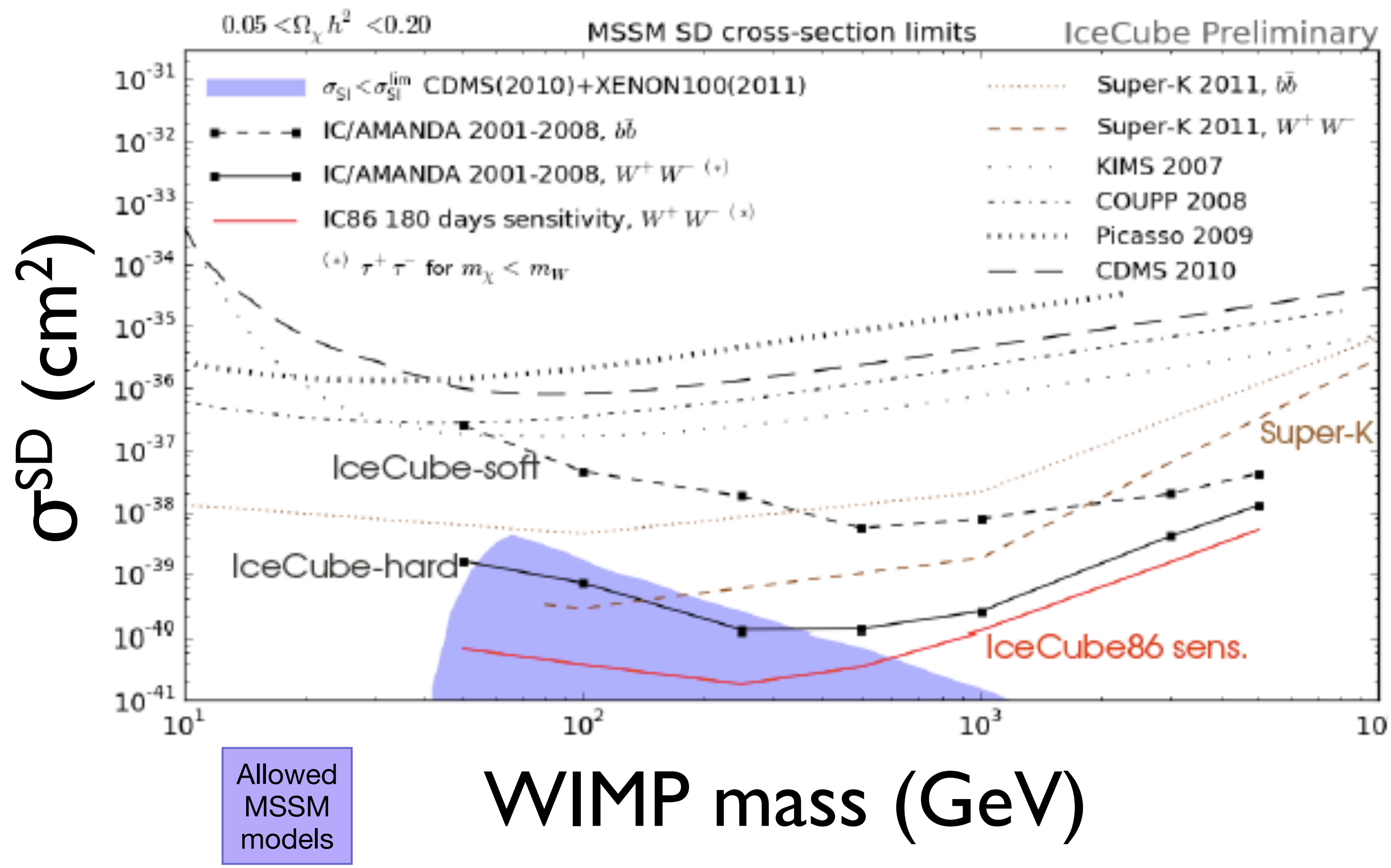
- Exploit asymmetries in the neutrino/anti-neutrino cross section, kinematics
- Effect is largest at energies below 5 GeV (for Earth diameter baseline)
- Control of systematics will be crucial

Recent results suggest that nature may be kind and provide a sufficiently large θ_{13}



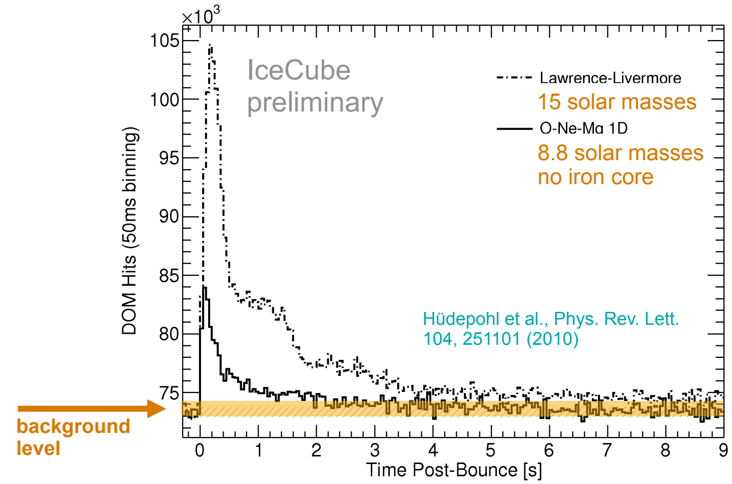
Deep Core: Predicted Performance: WIMPs

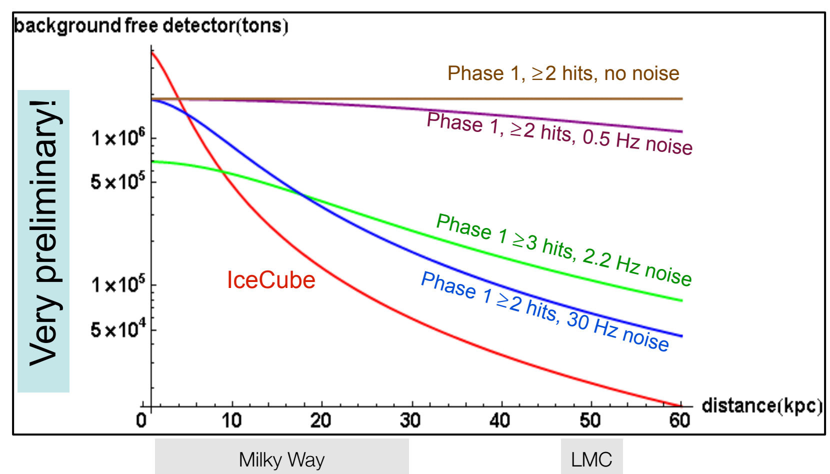
- Solar WIMP dark matter searches probe SD scattering cross section
  - SI cross section constrained well by direct search experiments
- DeepCore will probe large region of allowed phase space



PINGU-I:
Physics Motivations for ~1 GeV Energy Threshold

- Probe lower mass WIMPs
- Gain sensitivity to second oscillation peak/trough
  - will help pin down $(\Delta m_{23})^2$
- Gain increased sensitivity to supernova neutrino bursts
  - Extension of current search for coherent increase in singles rate across entire detector volume
  - Only 2±1 core collapse SN/century in Milky Way
    - need to reach out to our neighboring galaxies
  - Gain depends strongly on noise reduction via coincident photon detection (e.g., in neighbor DOMs)
- Begin initial *in-situ* studies of sensitivity to proton decay
- Technological R&D for PINGU-II





Equivalent size of a background free detector for beginning 0.38 s of **Lawrence Livermore** model, 1 m DOM and 10 m string distance, 18 strings (~6,000 DOMs) (figures from Lutz Koepke/Mainz)

Cost Basis: Drilling and Deployment

Drill Season Overhead	6	$1,000,000		$6,000,000
Hole Drilling	120	$300,000		$36,000,000
Cables	120	$100,000		$12,000,000
Total				$54,000,000

- Technical challenges of instrumenting Antarctic ice cap as a Cherenkov medium well understood
  - Static, low-background environment with existing infrastructure
- Instrumentation deployment now a routine process, achieved ~20 strings per season for last three years (18, 19, 20*)
  - Fuel consumption per hole substantially reduced over initial IceCube plan
  - Drill equipment suitable for continued use with minor refurbishment

Cost Basis: Optical Modules

	# Per OM	# Per String	Total	Cost Per Unit	Total Cost
PMTs	30	3,750	450,000	$350	$157,500,000
Electronics & Glass	1	125	15,000	$1,000	$15,000,000
OM and Electronics Development					$10,000,000

- Optical module cost estimate based on actual KM3NeT quotes (details not available, only an overall cost per OM)
- Included $10M for development, no other personnel included
- Contingency, management, etc. also not included – just the detector

Cost Estimate for a One Megaton Detector

- Costs are driven completely by total photocathode area
  - Is there a more cost-efficient way to collect Cherenkov photons?
- Costs seem competitive, even if management, contingency, personnel, etc. increase the total
- Scaling up to larger volume would be roughly linear in cost
  - Scaling *down* might be harder – how much photocathode can we pack in per unit volume?

Total Cost: $237M